Small-x physics with CMS at LHC

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on behalf of the CMS collaboration

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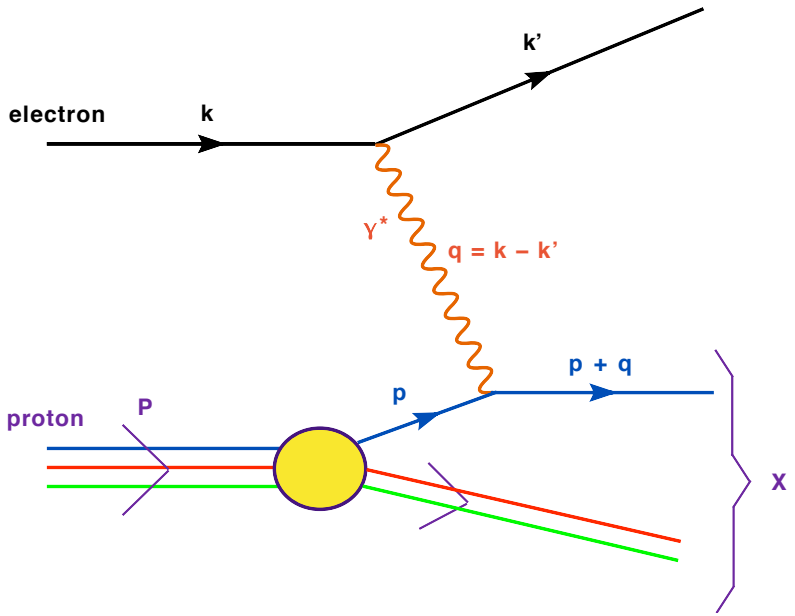
Many thanks to David d'Enterria and Forward PAG of CMS

Outline

Parton picture

- Probing parton distribution with **DIS**:
  - ↪ x: momentum **fraction** carried by parton
  - ↪ $Q^2 = -q^2$: **resolving** power



- QPM
  - static object composed of 3 valence quarks
  - no interaction between constituents
- QCD improved QPM
  - dynamic object with a very complicated structure
  - contains fluctuations smaller than its own size
- CGC
  - large densities of soft gluons
  - probe becomes more and more resolved
  - partons start overlapping and they recombine
  - non-linear evolution
- HERA results:
  - F_2 strongly rises at low x and Q^2
  - $\sigma_{tot}^{\gamma p} \sim (W^2)^{\lambda}$
  - $\lambda(Q^2)$

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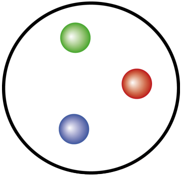

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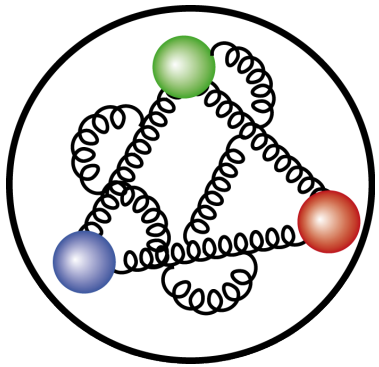

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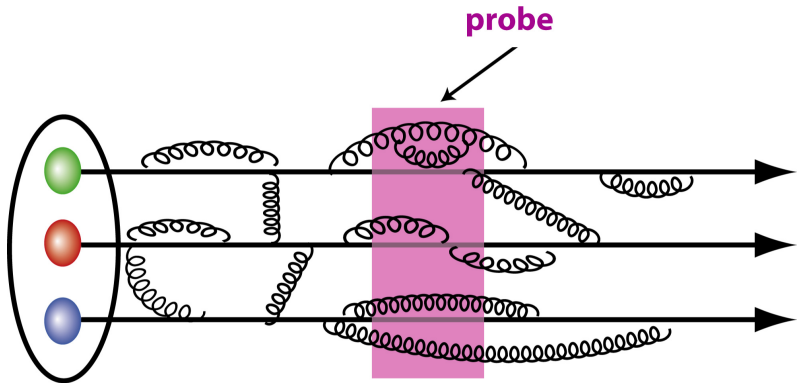

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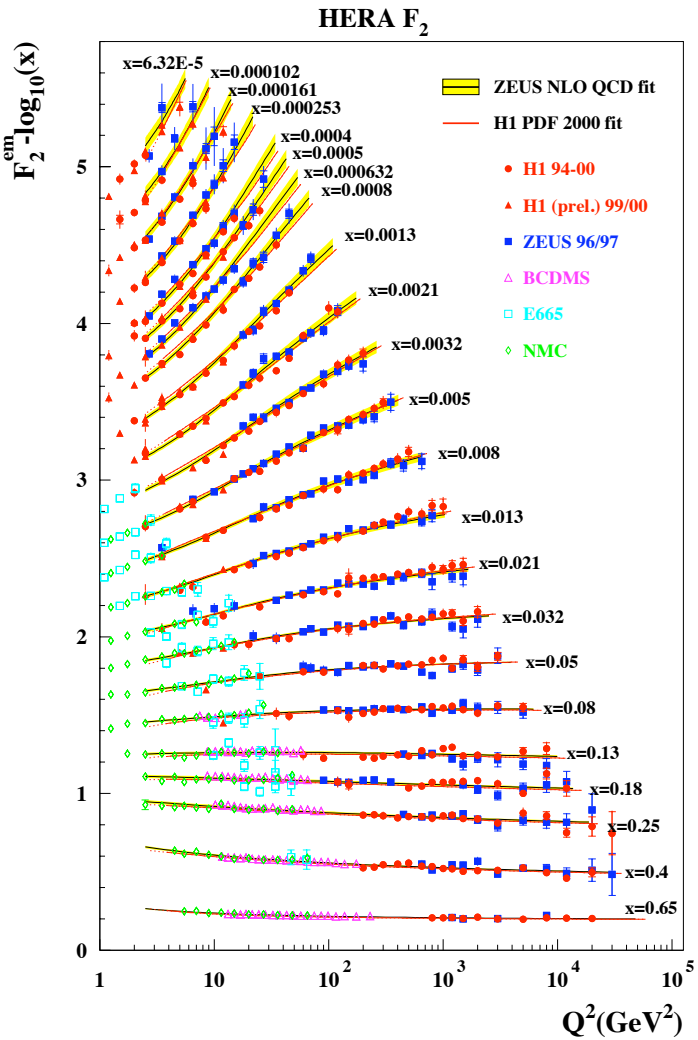

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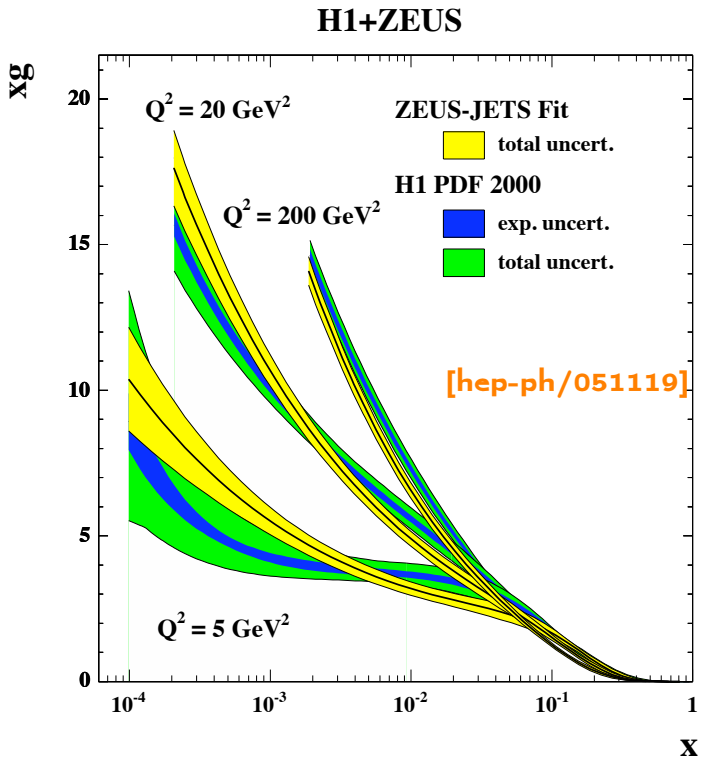


Parton (x, Q^2) evolution

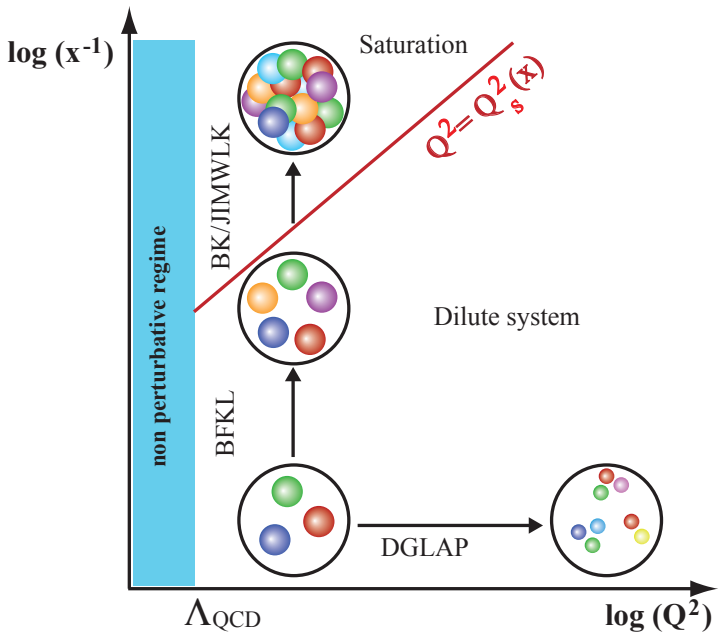
- **increasing Q^2** ($Q^2 > Q_s^2$): DGLAP $\Rightarrow$ evolution towards the **dilute** system
- **decreasing x ($Q^2 < Q_s^2$)**: BFKL $\Rightarrow$ evolution towards the **high density** system
- linear evolution equation doesn't work at low-x:
  - non-linear g+g fusion
  - unitarity violation

Saturation criterion

- number of partons per unit area $\rho \sim \frac{xG(x,Q^2)}{\pi R^2}$
- recombination cross-section $\sigma_{gg\to g} \sim \frac{\alpha_s}{Q^2}$
- recombination if $\rho\sigma_{gg\to g} \geq 1$ $(Q^2 \leq Q_s^2)$
- **saturation scale** $Q_s^2 \sim \frac{\alpha_s xG(x,Q_s^2)}{\pi R^2}$

CGC

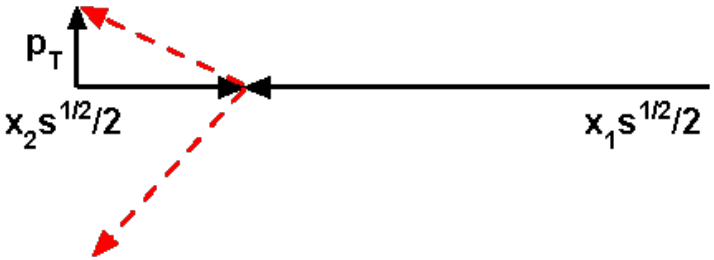
- effective field theory for high energy limit
- gluons overlap for momenta $\sim Q_s$
- non-linear JIMWLK evolution equation



Low-x PDF experimentally

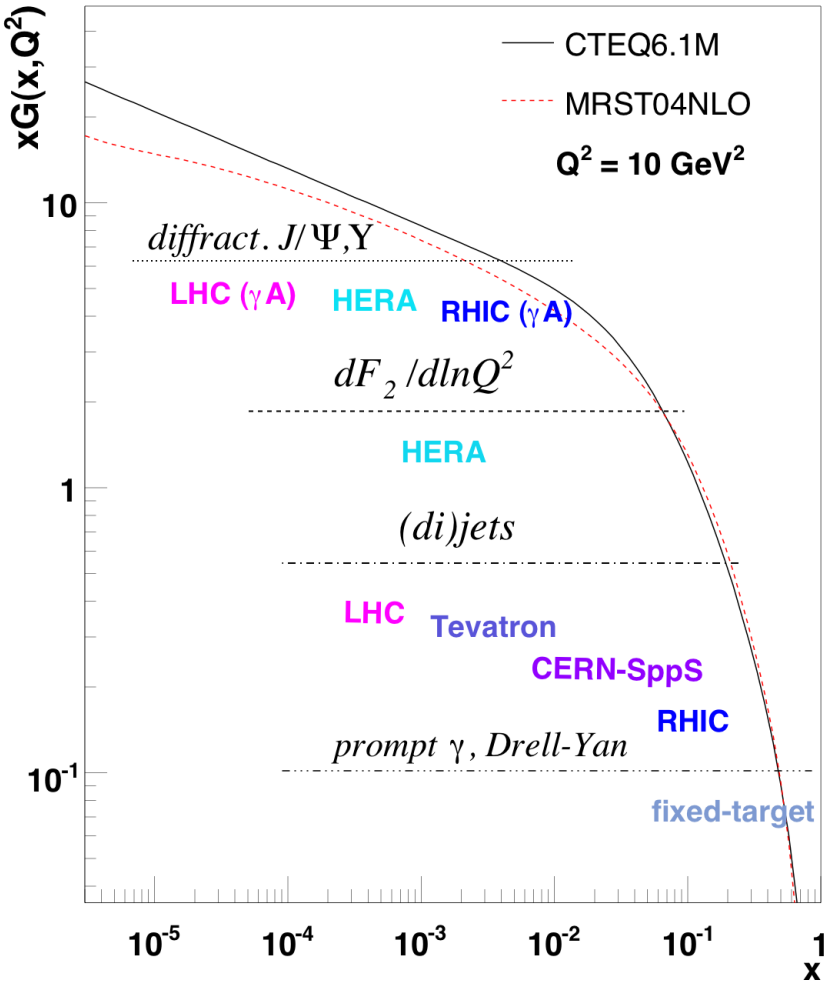
- low-x = forward rapidity

$$x_2^{min} \sim \frac{p_T}{\sqrt{s}} \cdot e^{-y} = x_T \cdot e^{-y}$$



every 2 units of y: x_2^{min} decreases by $\sim$10

- Processes:
  - Drell-Yan: p(p_1)+p(p_2)$\rightarrow l\bar{l}$+X
  - prompt-γ: p(p_1)+p(p_2)$\rightarrow$jet+γ+X
  - di(jets): p(p_1)+p(p_2)$\rightarrow$jet$_1$+jet$_2$+X
  - heavy Q: p(p_1)+p(p_2)$\rightarrow$Q+$\overline{Q}$+X
  - diffractive $Q\overline{Q}$ (γp, γA)



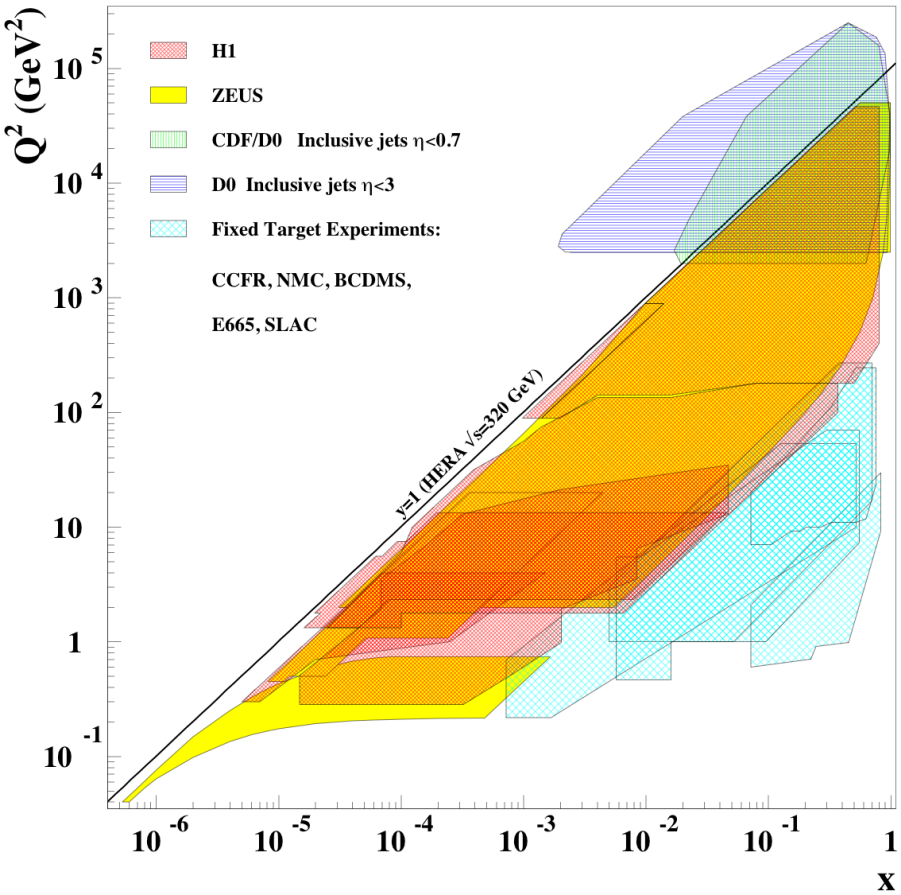
Low-x proton PDF

- most of our current knowledge comes from F_2 scaling violation:

$$\frac{\partial F_2(x,Q^2)}{\partial \ln(Q^2)} \propto \alpha_s(Q^2) x g(x,Q^2)$$

- large **uncertainties** for $x < 10^{-2}$ at moderate Q^2 (<5 GeV^2)

- **LHC**: p+p at 14 TeV
  - high $\sqrt{s} \Rightarrow$ very small x
    for $y <5$, M$<$10 GeV: $x \sim 10^{-6}$-10^{-7}
    (70 times lower than p+p at RHIC)
  - saturation momentum $Q_s \sim 2$ GeV
  - very large perturbative cross section



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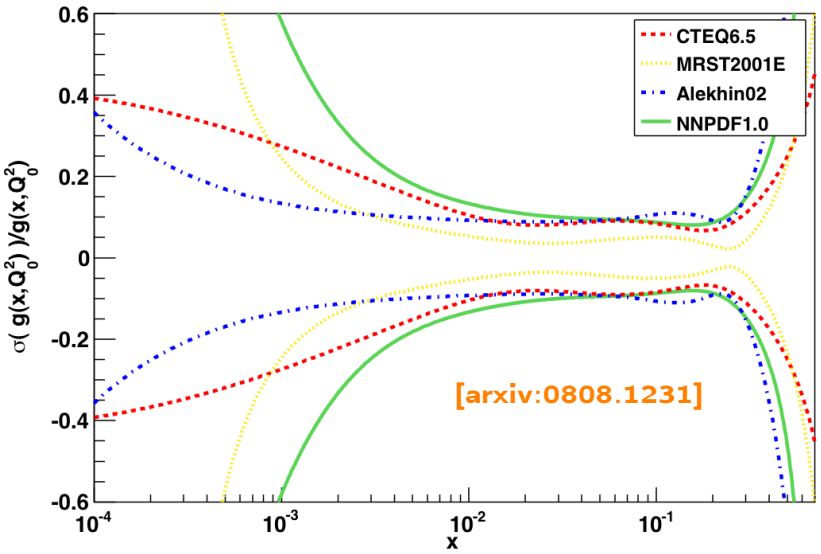
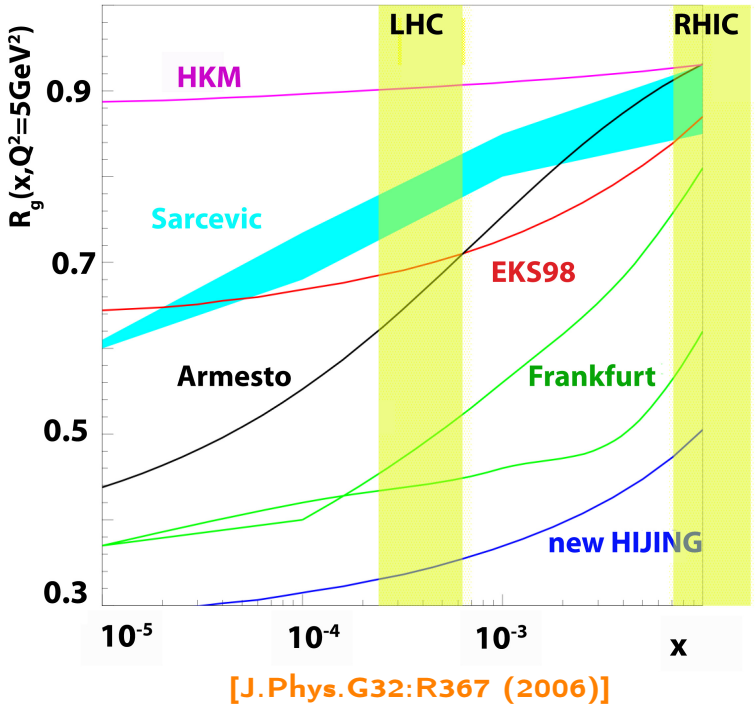


Low-x nuclear PDF

- current data from nuclear F_2 and nuclear Drell-Yan (eA)
- **DGLAP analysis**: linear evolution + nuclear shadowing
  - shadowing: low-x gluon fusion
  - shadowing factor for PDFs:
    $$R_g^A(x,Q^2) = \frac{f_g^A(x,Q^2)}{f_g(x,Q^2)}$$
- most data in **non perturbative** range (Q^2 <1-2 GeV^2): large uncertainties
- nuclear $xG(x,Q^2)$ **unknown** for x $<10^{-2}$
- **LHC**: Pb+Pb at 5.5 & p+Pb at 8.8 TeV:
  - x 30-45 times lower than Au+Au, d+Au at RHIC
  - saturation momentum Q_s ~3 GeV
  - very large perturbative cross section



[J.Phys.G32:R367 (2006)]

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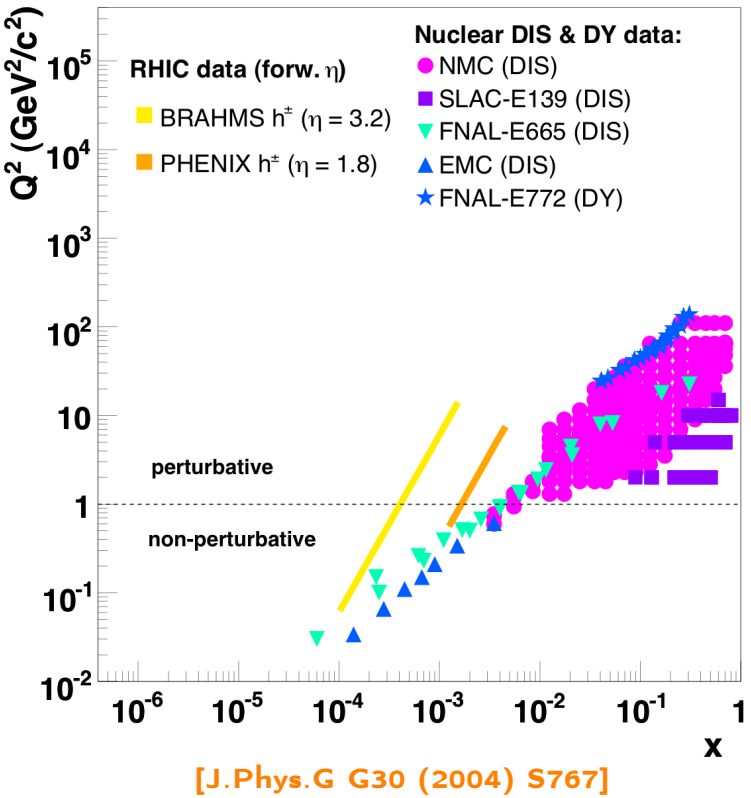

[J.Phys.G G30 (2004) S767]

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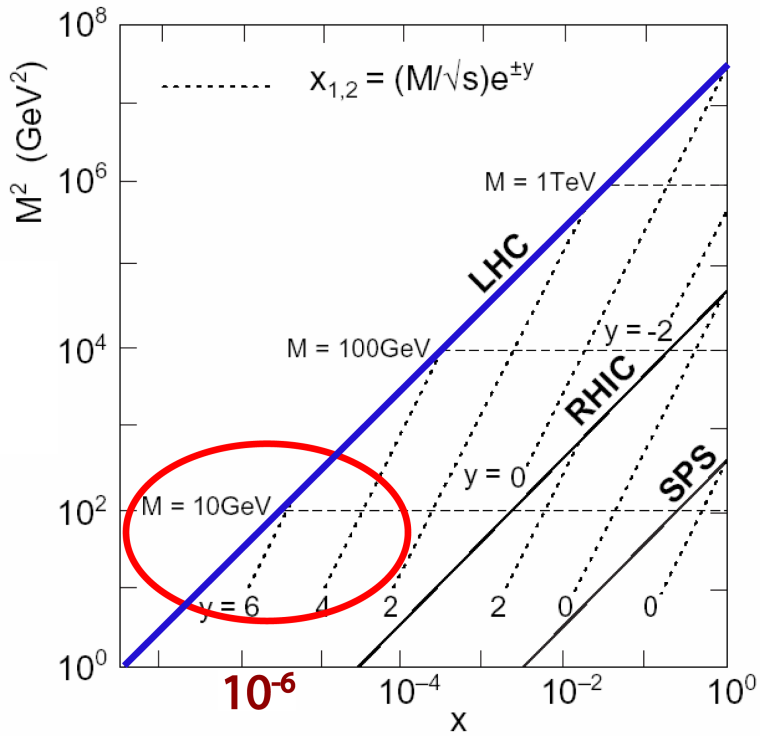
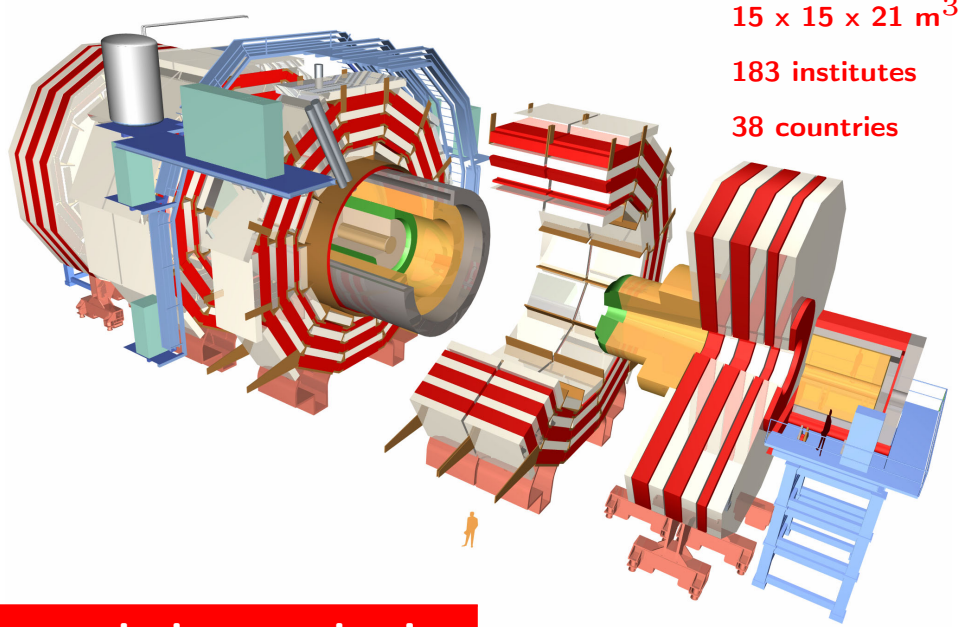


CMS experiment

CMS: dedicated to explore physics at the **TeV scale**

- **prime** goals: mechanism of electroweak symmetry breaking and provide evidence of physics beyond SM
- also **SM** measurements : QCD, B-physics, diffraction, top quark, and electroweak physics topics such as the W and Z boson
- Detector:
  - inner **tracking** system ($|\eta|$ <2.5)
  - **calorimeters** (electromagnetic: $|\eta|$ <3, hadronic: $|\eta|$ <5)
  - **muon** system ($|\eta|$ <2.4)
  - few **forwards** detectors (CASTOR: -6.6< η <-5.2 and ZDC: $|\eta|$ >8.3)



~ 2000 members

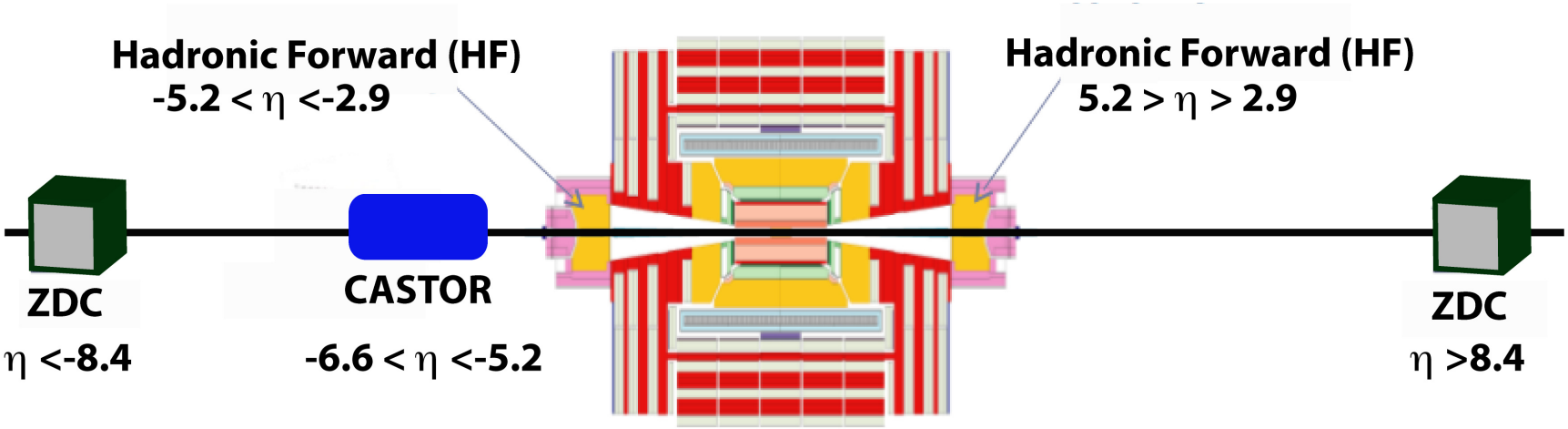
15 x 15 x 21 m^3

183 institutes

38 countries

Ideally suited to study low-x physics

Going forward: detectors



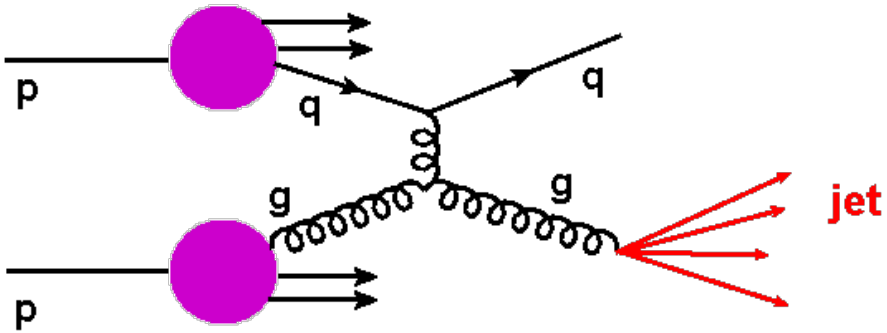
- HF
  - rapidity coverage: $2.9 < |\eta| < 5.2$
  - at 11.2 m from IP
  - steel absorbers and embedded radiation -hard quartz fibers for fast collection of Cherenkov light
  - segmentation in η et ϕ: 0.175 $\times$ 0.175
- CASTOR
  - rapidity coverage: $-6.6 < \eta < -5.2$
  - at 14.3 m from IP
  - alternate tungsten absorbers and quartz plates
  - segmentation in ϕ: 16 sectors
  - 14 modules (2EM+12HAD)
- ZDC
  - rapidity coverage: $|\eta| > 8.4$
  - at 140 m from IP
  - tungsten/quartz Cherenkov calorimeter with separated EM and HAD sections
  - detection of neutrals (γ, π^0, n)

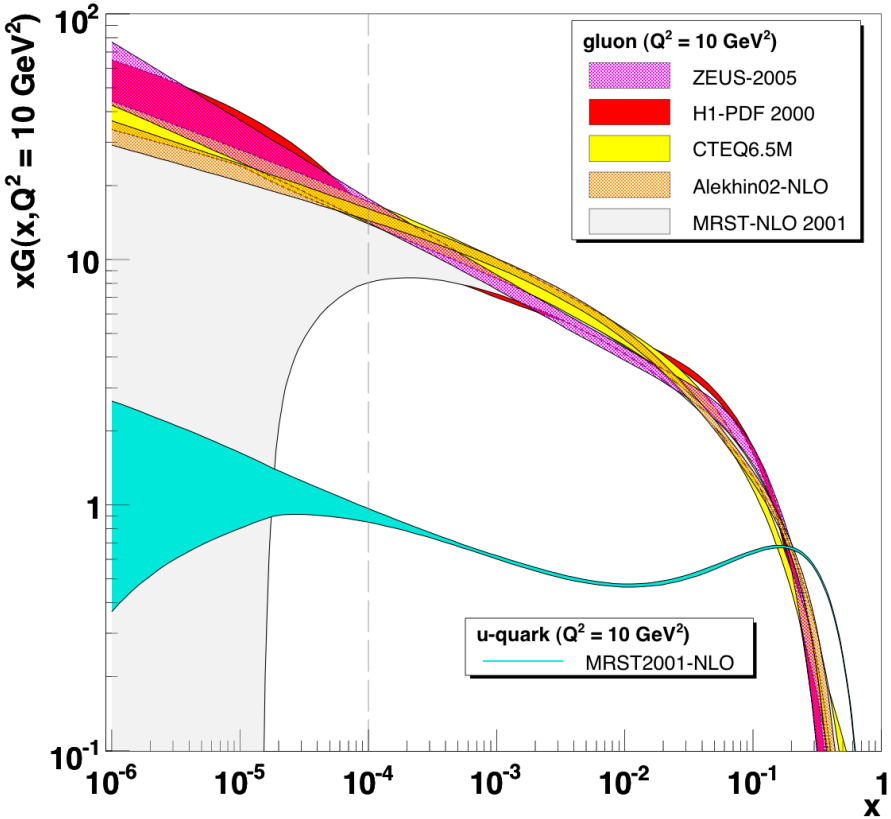
CMS $\Rightarrow$ unprecedented calorimetric coverage in pseudo-rapidity

p+p collisions

p+p: forward jets

- **Low-x gluon** density in the proton is poorly known ($x = \mathrm{p}_{parton}/\mathrm{p}_{hadron}$)
- Forward jet production in **CMS calorimeters**:
  - HF: $x \sim 10^{-4}$
  - CASTOR: $x \sim 10^{-5}$
- **Forward** jet cross-sections **constrain low-x gluon** PDFs





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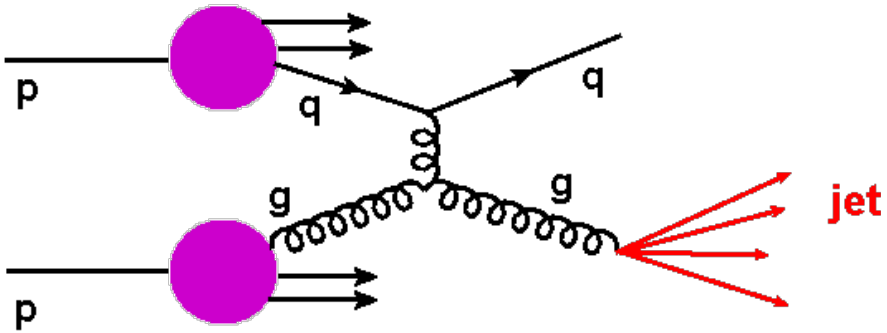

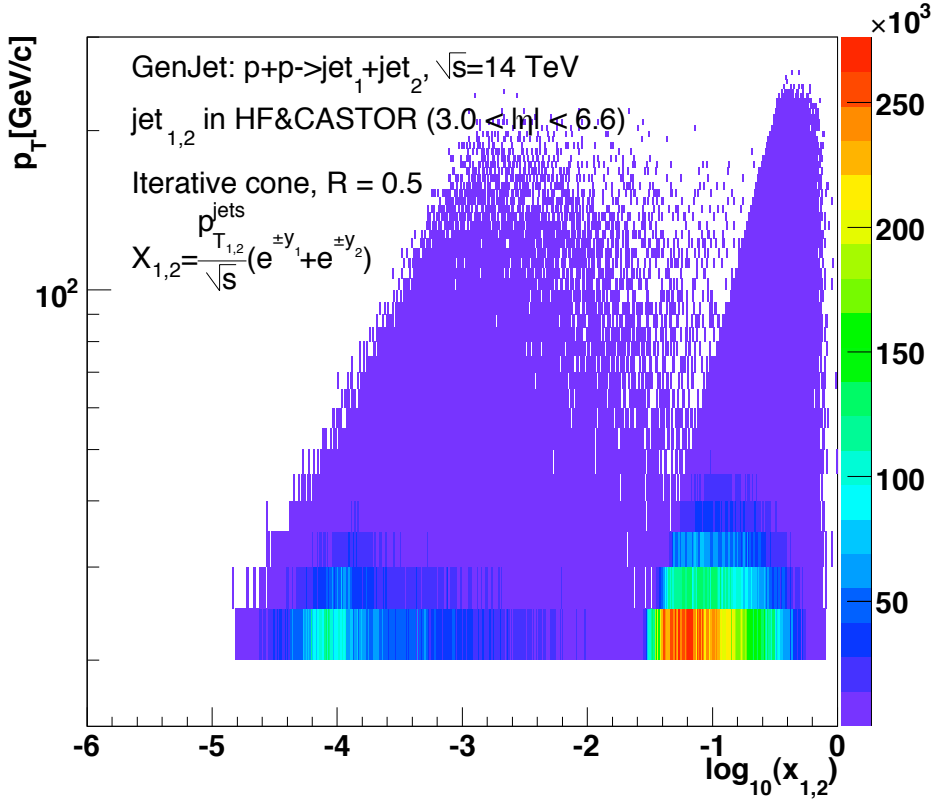

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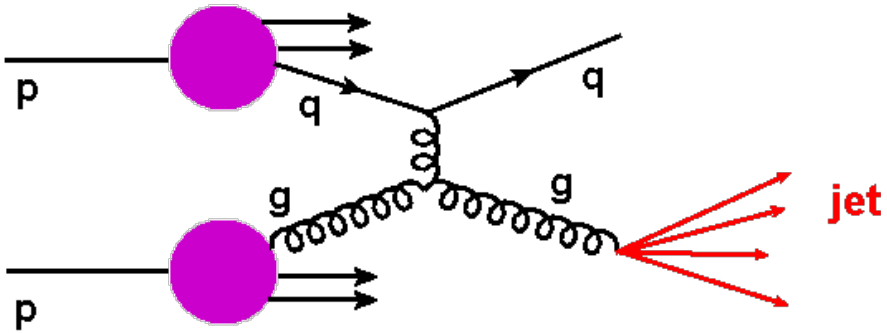

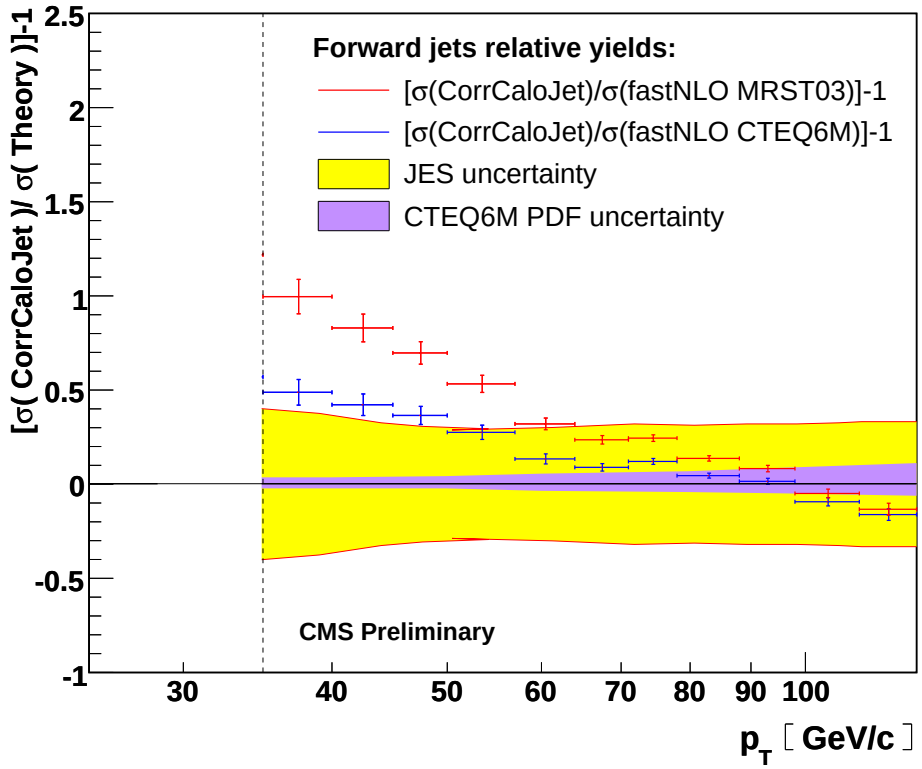

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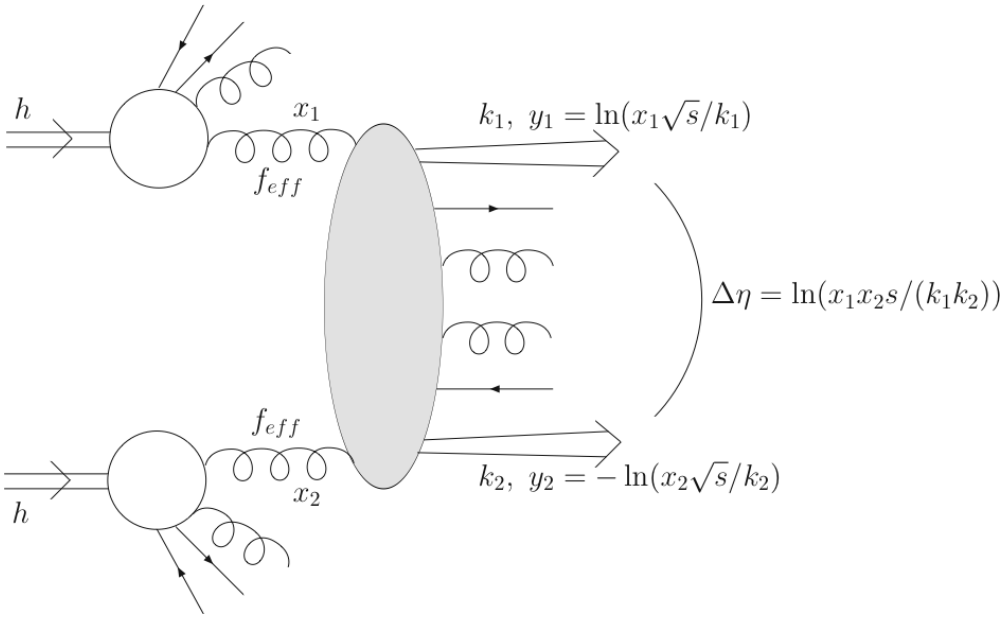
p+p: Mueller-Navelet dijets

- **Mueller-Navelet dijets** with large η separation very sensitive to **low-x QCD** evolution (testing ground for BFKL)
  - **BFKL**: extra radiation between the 2 jets will **smear out** back-to-back topology
  - enhanced radiation partially compensated by gluon saturation ?



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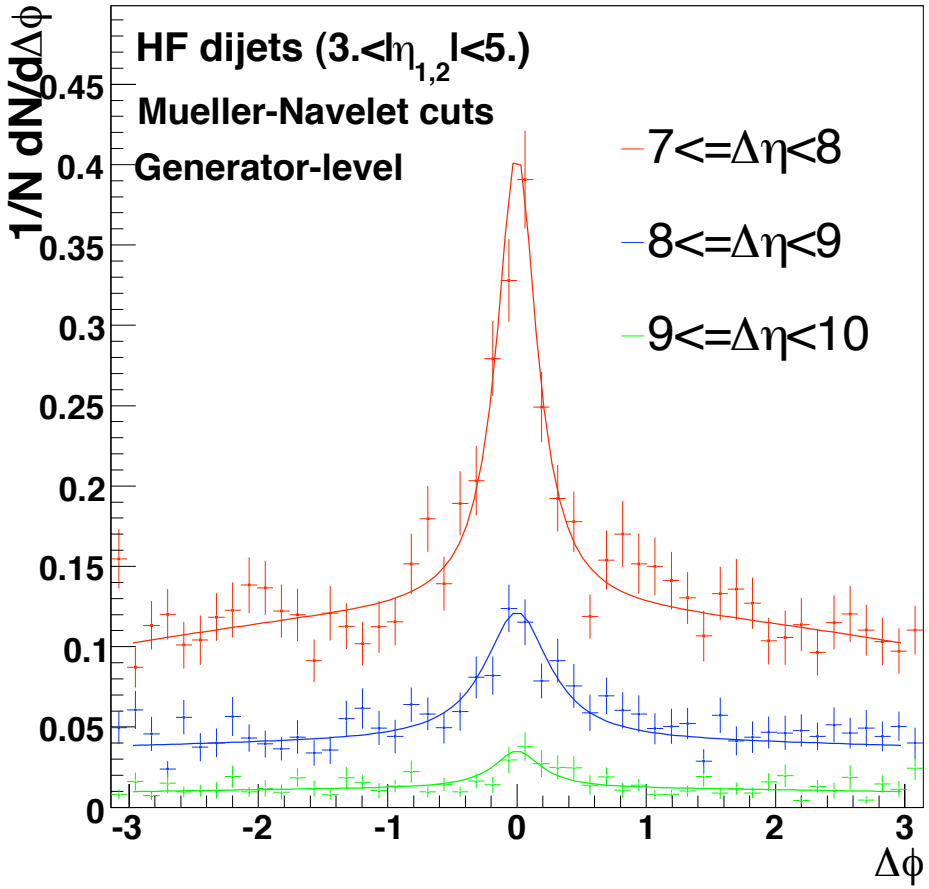

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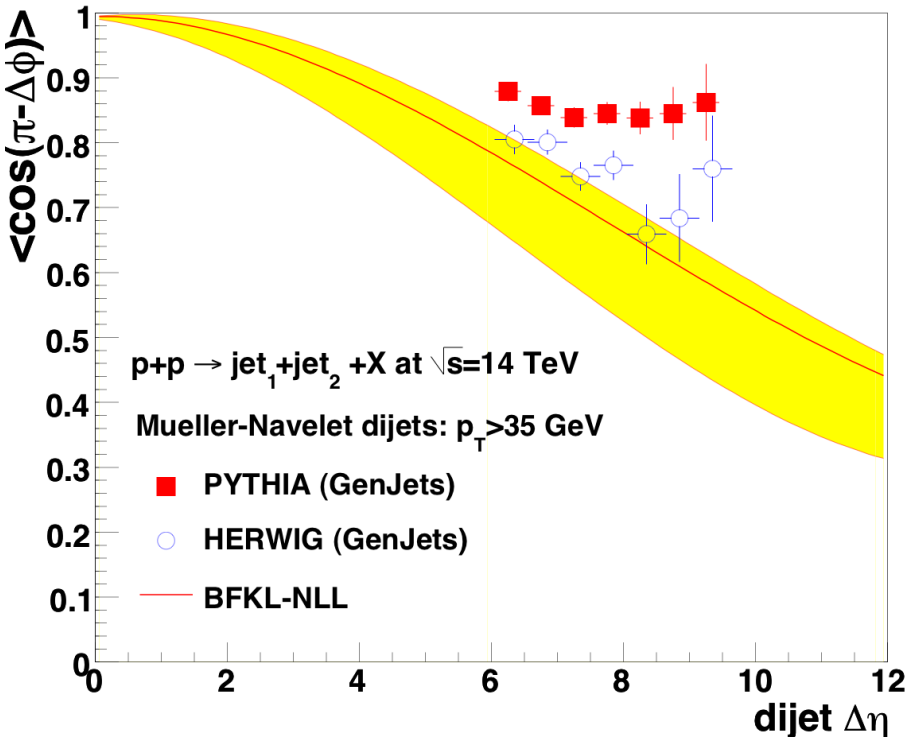
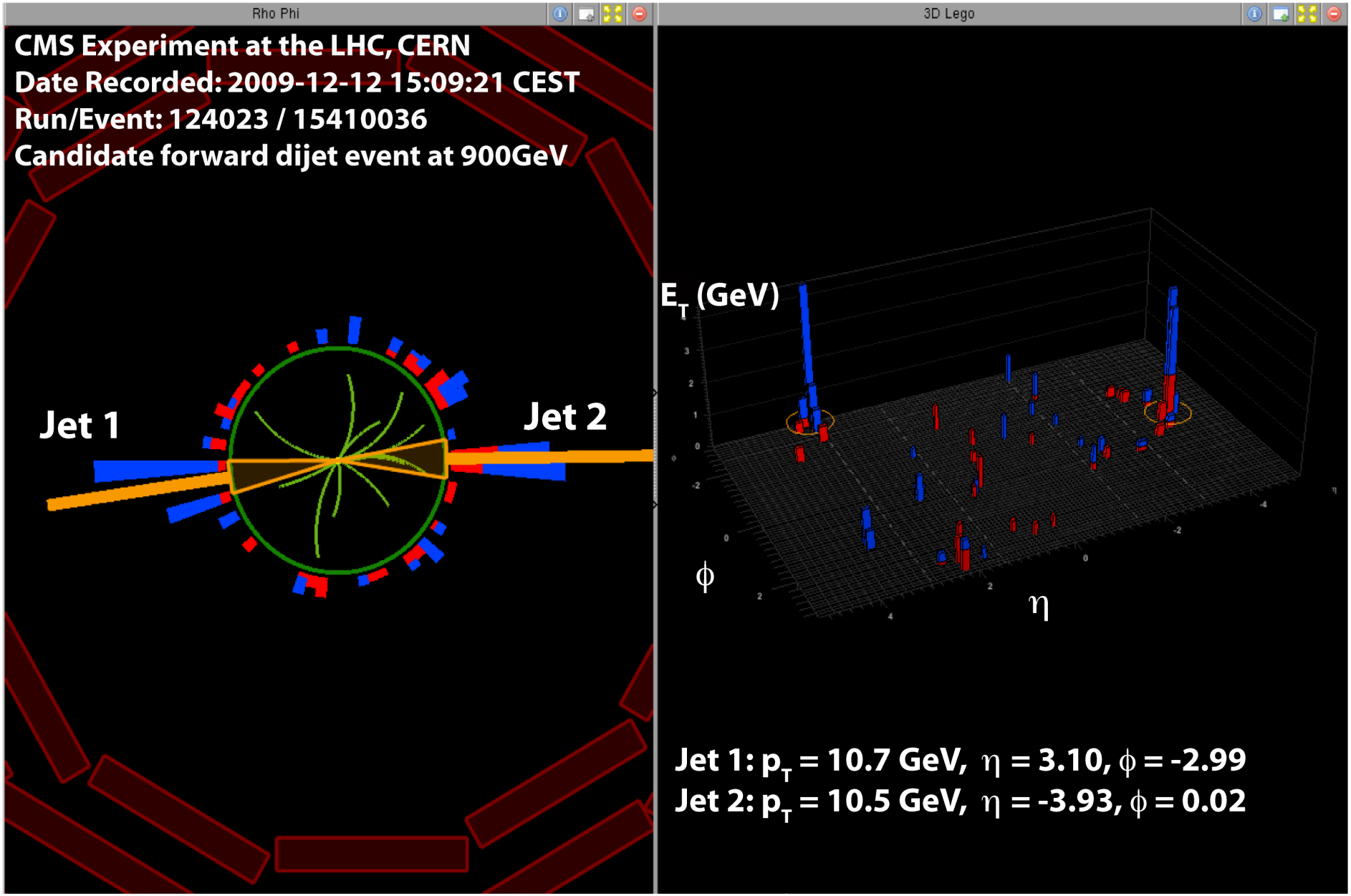


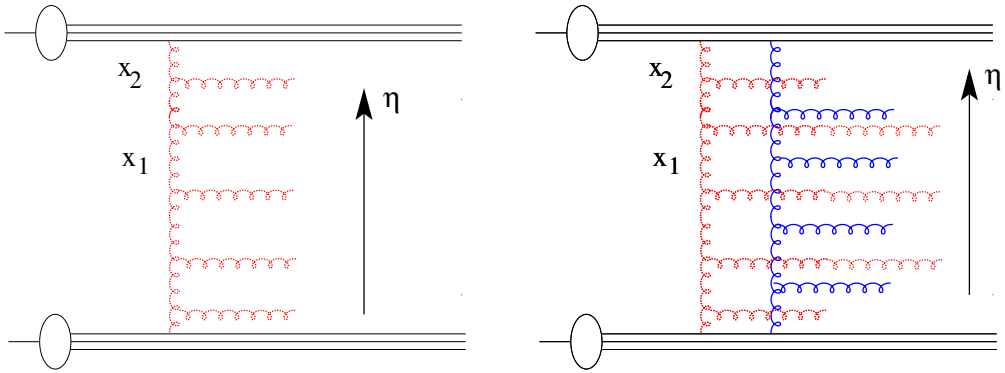
Dedicated HLT trigger !

p+p: First candidate for Mueller-Navelet dijets in 900 GeV data !



p+p: Forward energy flow: Motivation

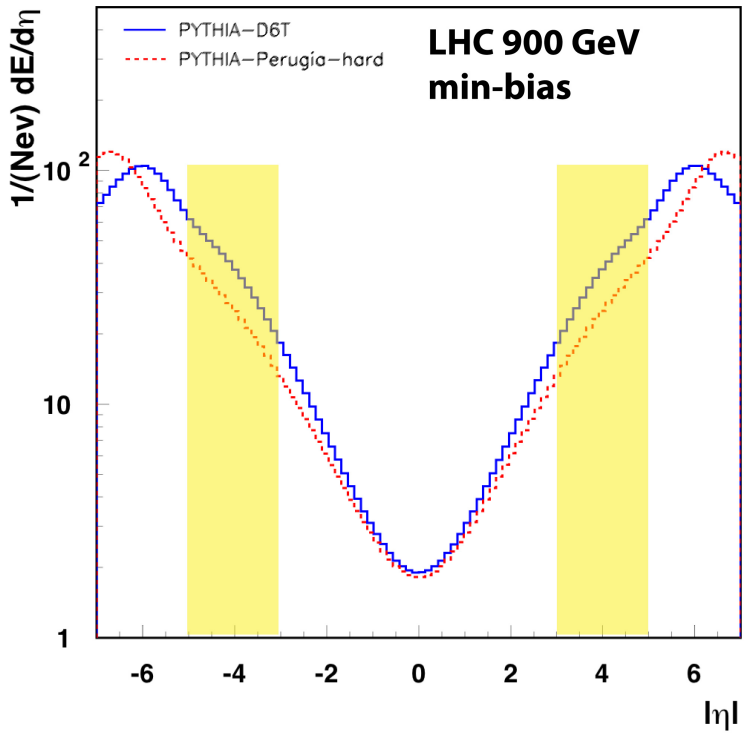
- improve the understanding of the **parton radiation** in the initial state
- study the **multiparton interactions**
- implemented in Monte Carlo event generators: need **parameters** to be adjusted to describe the measurements
- the extrapolation to larger energies is **very uncertain**
- it probes **underlying event** in a new way

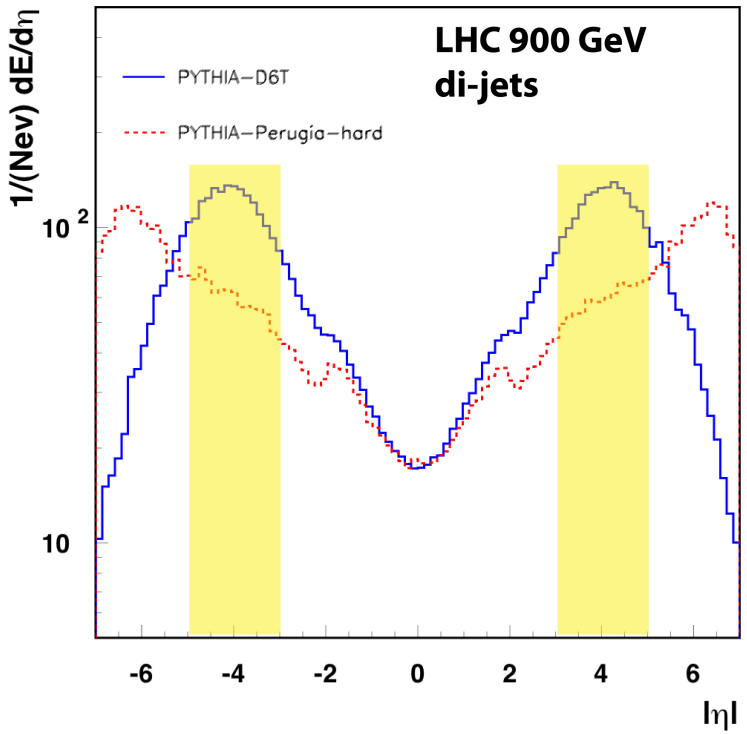


The energy dependance of multiple parton interactions is not well known yet !

p+p: Forward energy flow: Predictions

- comparison of two different tunes: Pythia-D6T (CTEQ6L1) and Pythia-Perugia (CTEQ5L)
- energy flow in **central** region at low $\sqrt{s}$ does **not** change much with tunes
- significant difference observed in the **large pseudorapidity** region ($|\eta| > 2$)





Energy flow in the forward region ⇒ has never been measured at a hadron collider

p+p: Forward energy flow: First look on the real data !

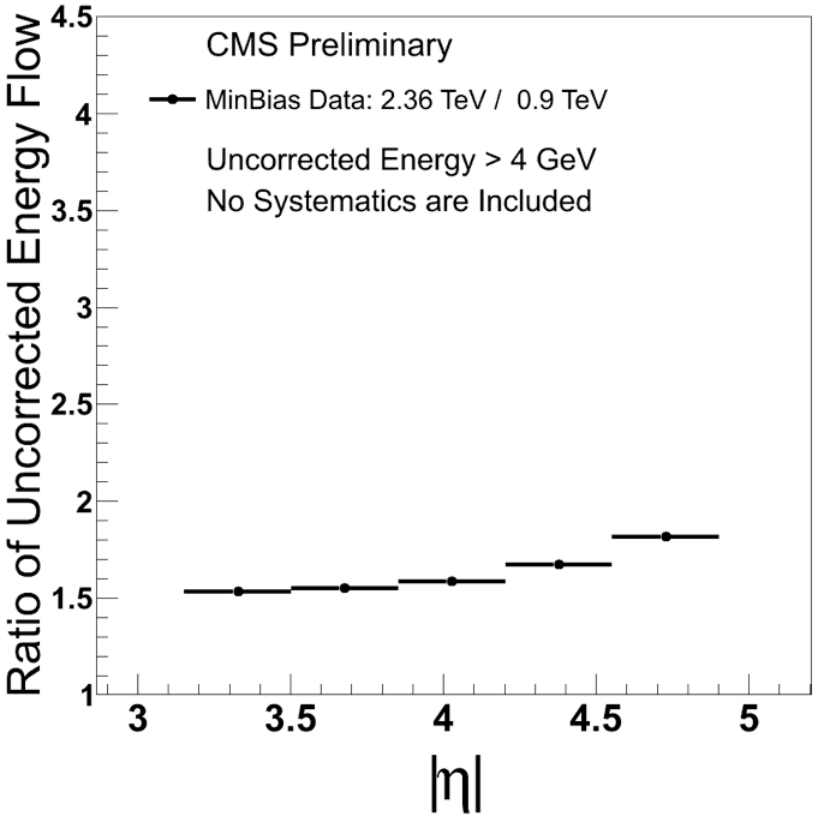
- **Event** selection
  - min-bias trigger
    - Beam Pick-up Timing for the eXperiments (BPTX): provide the information on the bunch structure and timing of the incoming beam with the precision better than 0.2 ns
    - Beam Scintillator Counters (BSC): provide hit and coincidence rates
    - rejection of beam halo events
  - rejection of non-IP events: require at least 10 tracks with 25% of the tracks to be high purity
  - at least one primary vertex reconstructed with number of tracks > 3 with $|z| < 15$ cm (distance to the CMS IP) and impact parameter $d_0 \leq 2$ cm
- **Energy flow** ratio definition

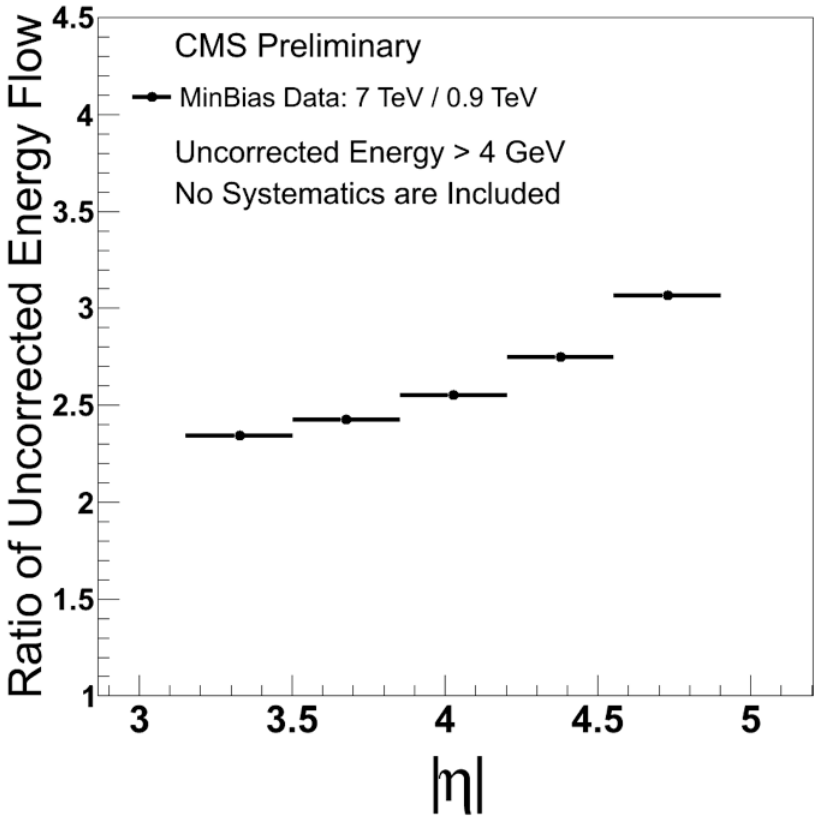
$$R_{Eflow}^{\sqrt{s_1},\sqrt{s_2}} = \frac{\frac{1}{N_{\sqrt{s_1}}}\frac{\Delta E_{\sqrt{s_1}}}{\Delta\eta}}{\frac{1}{N_{\sqrt{s_2}}}\frac{\Delta E_{\sqrt{s_2}}}{\Delta\eta}}$$

where
$\sqrt{s_1} = 2.36$ or 7 TeV
$\sqrt{s_2} = 0.9$ TeV
$N_{\sqrt{s}}$: number of selected minimum bias events for given energy
$\Delta E_{\sqrt{s}}$: energy deposited in a region in $\Delta\eta$ for a given energy (integrated over azimuthal angle)

p+p: Forward energy flow: Results !

- results on the **detector level**, **no systematics** uncertainties included

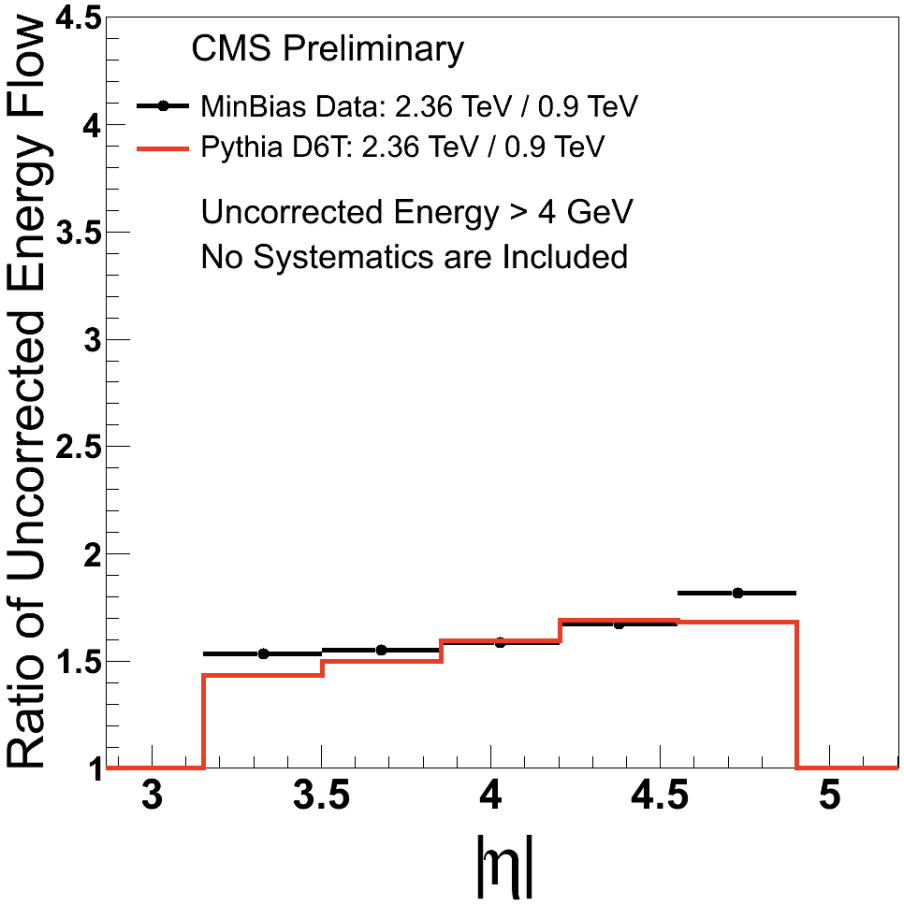


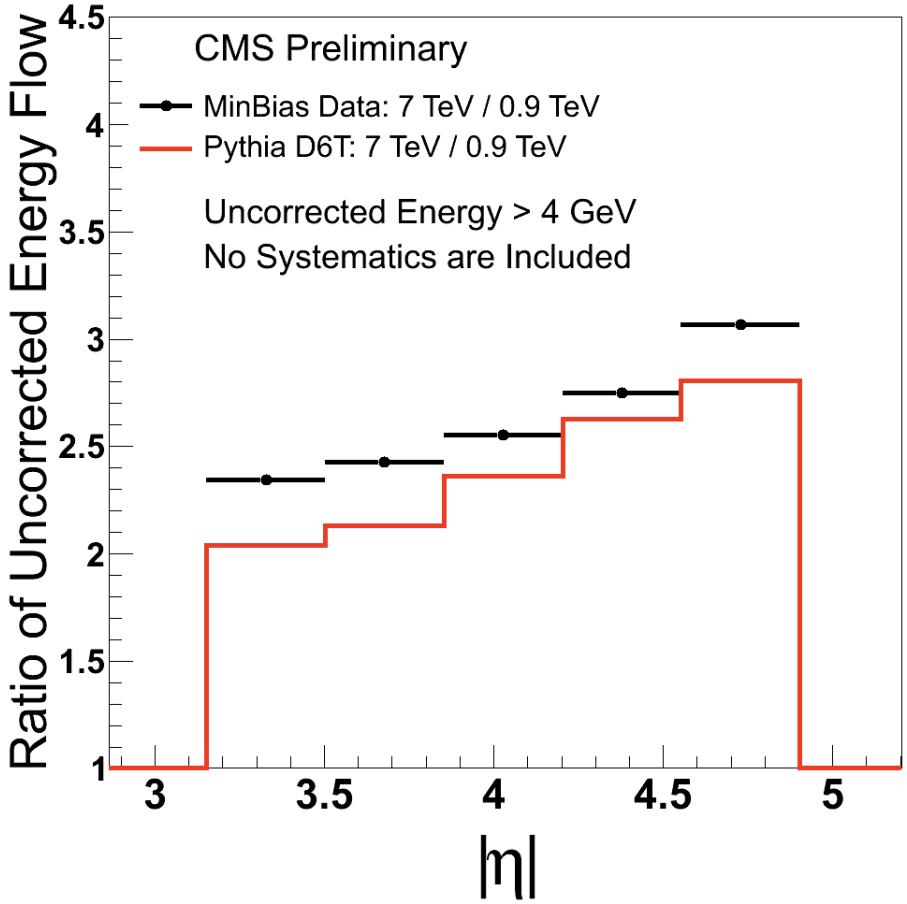


- **more energy** deposited when increasing energy
- **more energy** deposited in the **large** η region
- conclusion on the quality of the description **can't** be made without the systematics uncertainties

p+p: Forward energy flow: Results !

- results on the **detector level**, **no systematics** uncertainties included





- **more energy** deposited when increasing energy
- **more energy** deposited in the **large** η region
- conclusion on the quality of the description **can't** be made without the systematics uncertainties

p+p: Forward energy flow: Conclusions

- CMS is working very well
- First measurement of energy flow in the forward region was performed
- First results are very encouraging
- Input to Monte Carlo simulations
  - include the systematics
  - can be used for the MC tuning
  - can teach us more about small-x evolution and parton radiation

LHC opened a new phase space for small-x physics studies

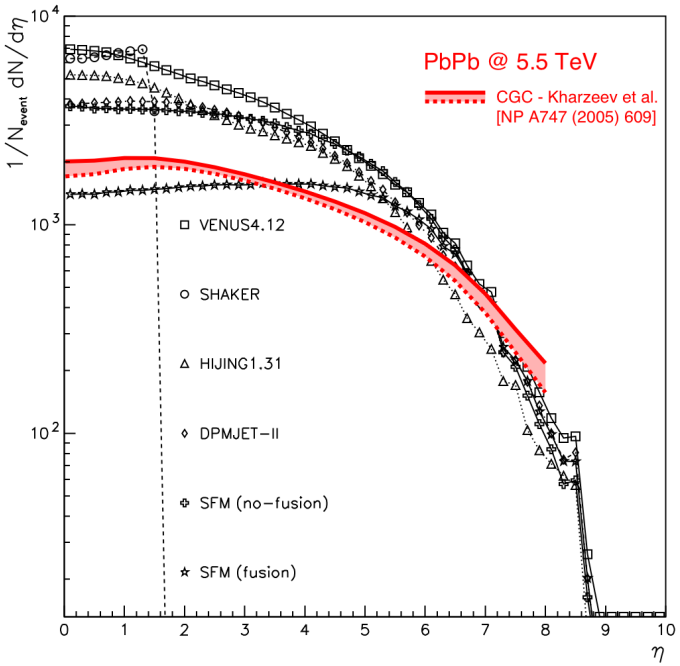
Pb+Pb collisions

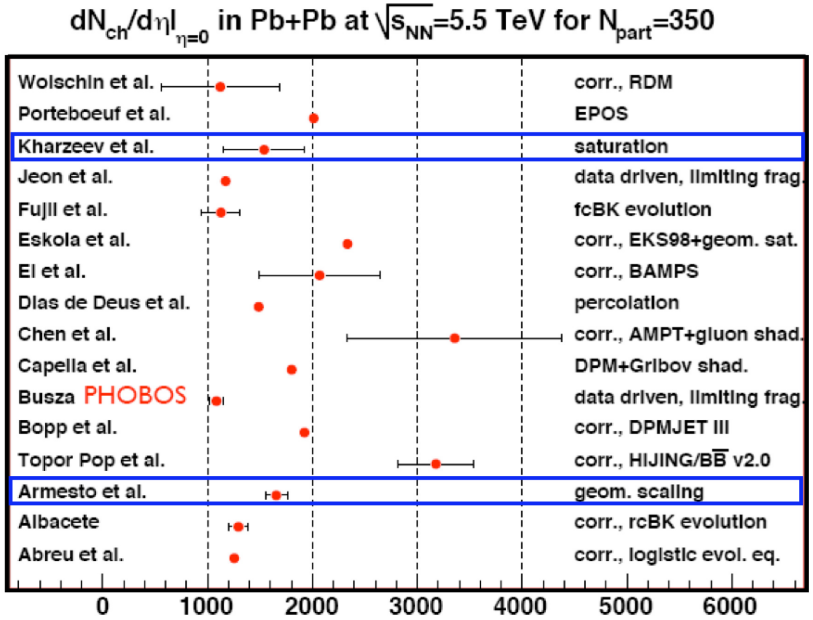
Pb+Pb: total hadron multiplicity

- final **hadron** rapidity **density** $\propto$ number of **initially** release **partons** at a given η

$$\frac{dN}{d^2b d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x, Q_s^2) \cdot A^{1/3}$$

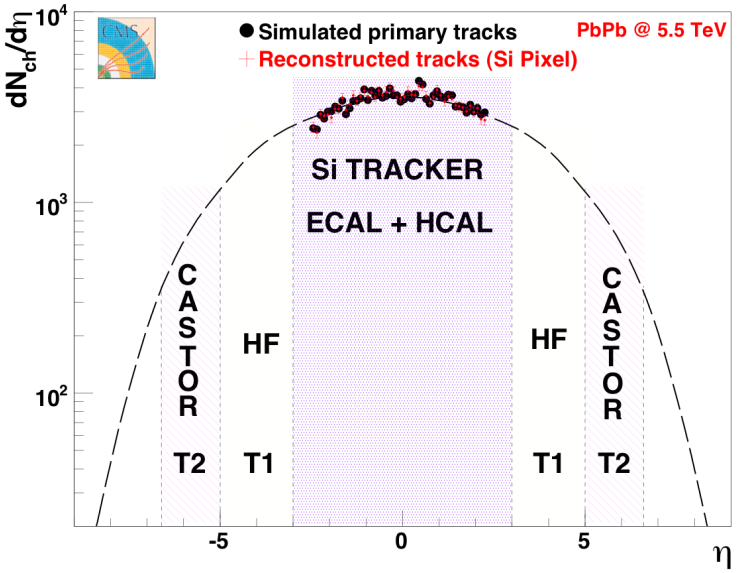
- **reduced** multiplicity predicted by saturation models: **gluon recombination** reduces incoming parton flux
- **saturation** driven predictions for LHC: $dN/d\eta(\eta{=}0) \sim 2000$ (8000 before RHIC results)

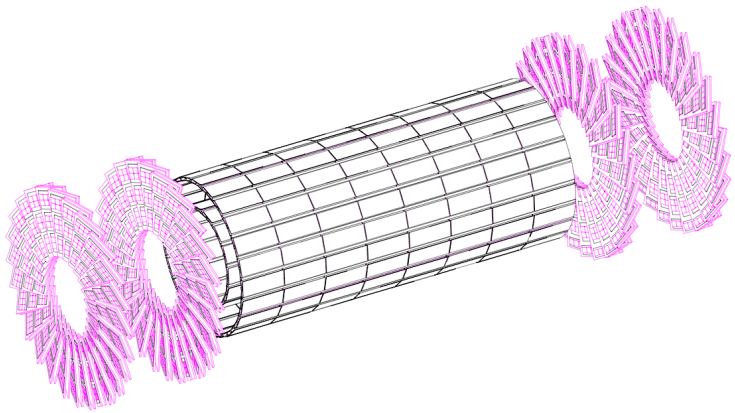




Pb+Pb: multiplicity with CMS

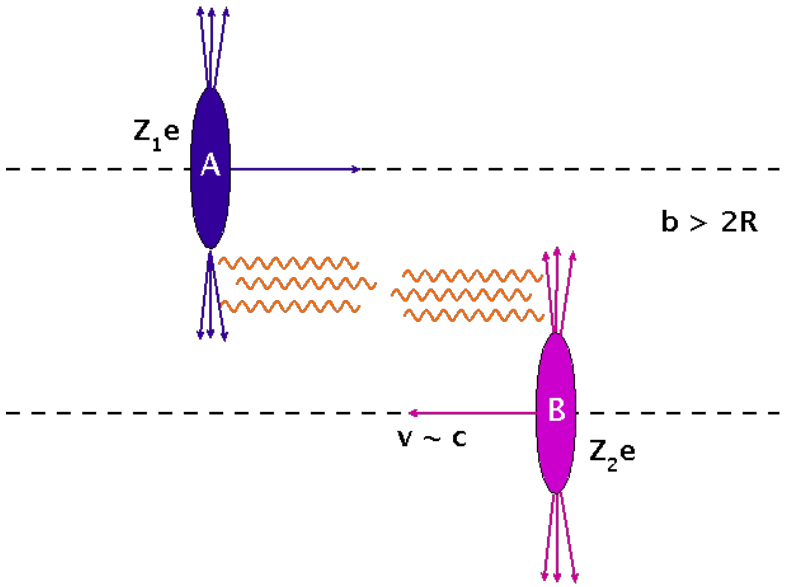
- **day-1** measurement !
- method: **hit counting** in the pixel tracker
  $|\eta|$ <2.5
- CMS Si **pixel tracker**:
  - 3 layers 53.3 cm long barrel layers (innermost barrel radius of 4.4 cm)
  - 2 end-cap disks
  - full ϕ
  - pixel size (z $\times$ r) = 100 $\times$ 150 μm
- resolution
  - impact parameter: $\sim$100 μm
  - p_T: $\sim$ 0.7 % for 1 GeV (η=0)

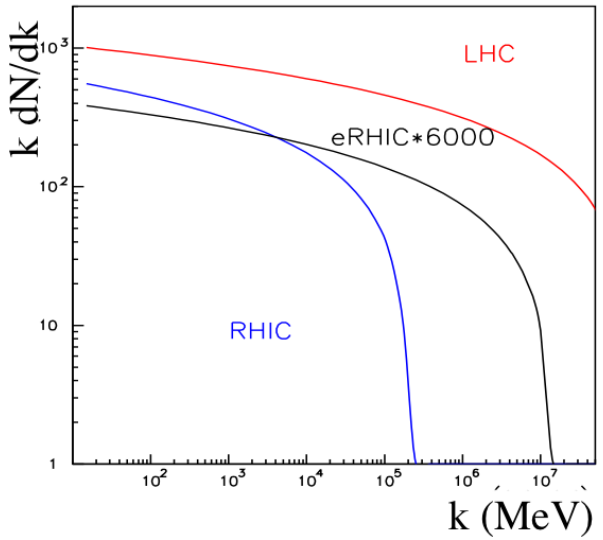




Pb+Pb: Photon beams at the LHC

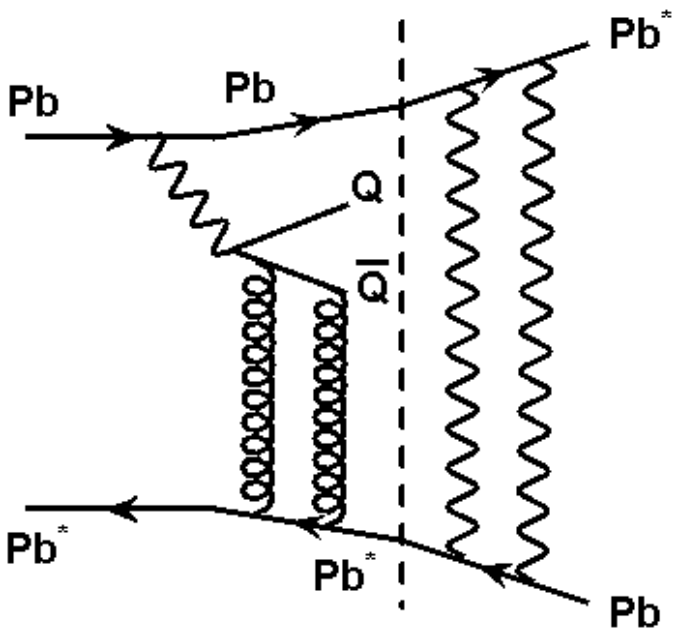
- Weizsacker-Williams (EPA):
  - **electromagnetic field** (coherent action of Z=82 proton charges)
  - generated equivalent **flux of photons**
- characteristics of **Ultra-Peripheral Collisions** (UPC)
  - $b_{min} \sim 2R_A$: nuclei do not collide $\Rightarrow$ γ-induced reactions
  - γ-flux $\sim Z^2$: **enhancement** factor of 7000 is expected for Pb beam (if compared to electron or proton beam)
  - Max photon energy: $\omega_{max} \approx \gamma/R_A$ ~3 (80) GeV for Au+Au RHIC (Pb+Pb LHC)
  - max center of mass energy for γ+Pb collisions:
    - $\sqrt{s}_{\gamma+Pb} \approx$ 30 (900) GeV for Au+Au RHIC (Pb+Pb LHC)
    - LHC $\sim$ 3-4 $\sqrt{s}_{\gamma+p}$ at HERA
  - coherence condition $\Rightarrow$ very **low** γ **virtuality**: production of **low** transverse momenta particles ($\sim$ 30 MeV)

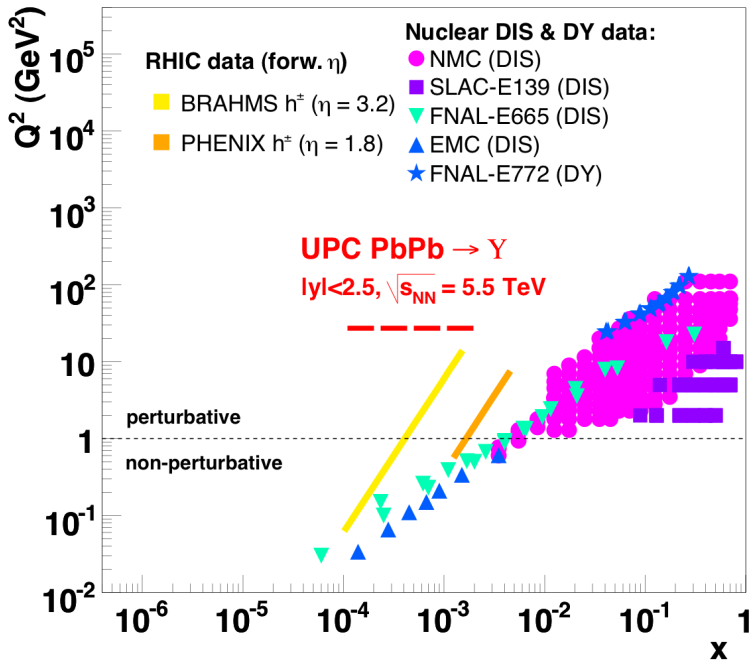




Pb+Pb: $Q\overline{Q}$ photoproduction in UPC

- sensitive to the **square of the gluon density** in the nucleus
  $\frac{d\sigma_{\gamma p,A\to V_{p,A}}}{dt} = \frac{\alpha_s^2\Gamma_{ee}}{3\alpha M_V^5}16\pi^3[xG(x,Q^2)]^2$ with $Q^2 = M_V^2/4$ and $x = M_V^2/W_{\gamma p,A}^2$
- x probed in γ+A $\Rightarrow$ Υ+A process at LHC:
  - for y=0: $x \approx 2\cdot$ **10^{-3}**
  - for y=2.5: $x \approx [x(y=0)]\cdot e^{-y} \approx$ **10^{-4}**
- available (x,Q^2) regime to constraint the **nuclear PDFs**
- **Unexplored** (x,Q^2) can be studied !

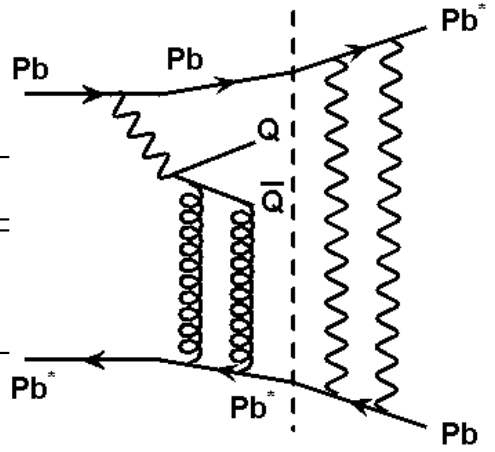




Pb+Pb: UPC γPb$\rightarrow \Upsilon$: cross section prediction

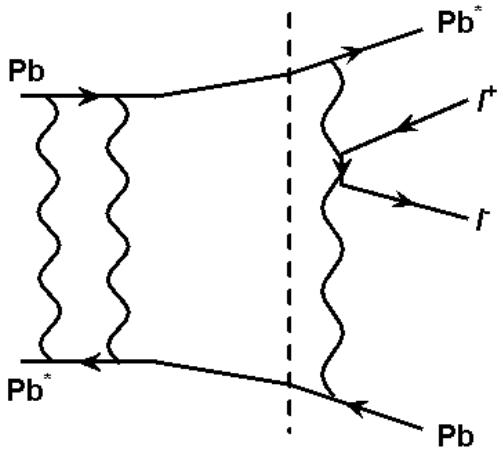
- STARLIGHT Monte Carlo predictions: **signal**

Process	σ_{tot}	σ_{X_n}	$\sigma_{X_n \vert X_n}$
Pb+Pb$\rightarrow \gamma$+Pb$\rightarrow$J/ψ+X	32 mb	8.7 mb	2.5 mb
Pb+Pb$\rightarrow \gamma$+Pb$\rightarrow \Upsilon(1S)$+X	173 μb	78 μb	25 μb



- **background**: coherent production of lepton pairs in two-photon processes

Process	$\gamma\gamma \rightarrow e^+e^-$	$\gamma\gamma \rightarrow \mu^+\mu^-$
σ(m$_{inv}$ >1.5 GeV)	139 mb	45 mb
σ(m$_{inv}$ >6 GeV)	2.8 mb	1.2 mb



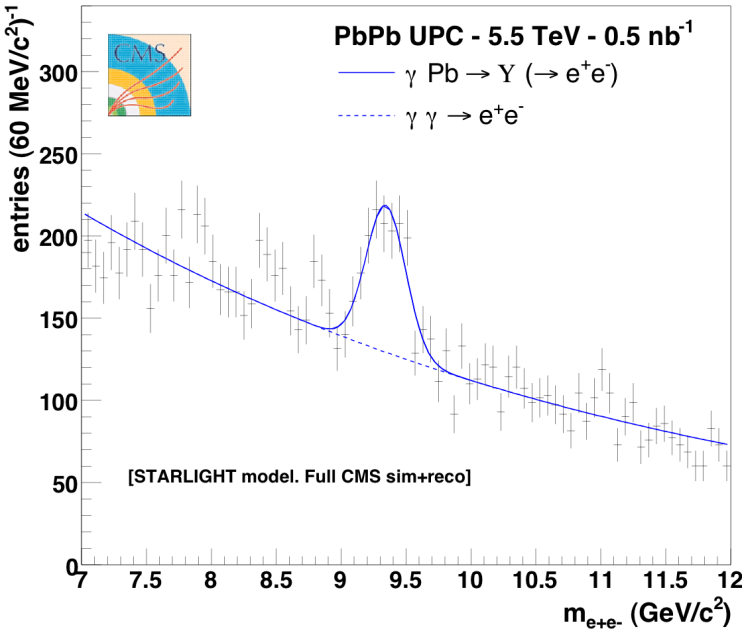
- ~50 % of UPC interactions lead to the nuclear breakup with forward neutron emission (X$_n$)

Pb+Pb: Study from the simulation

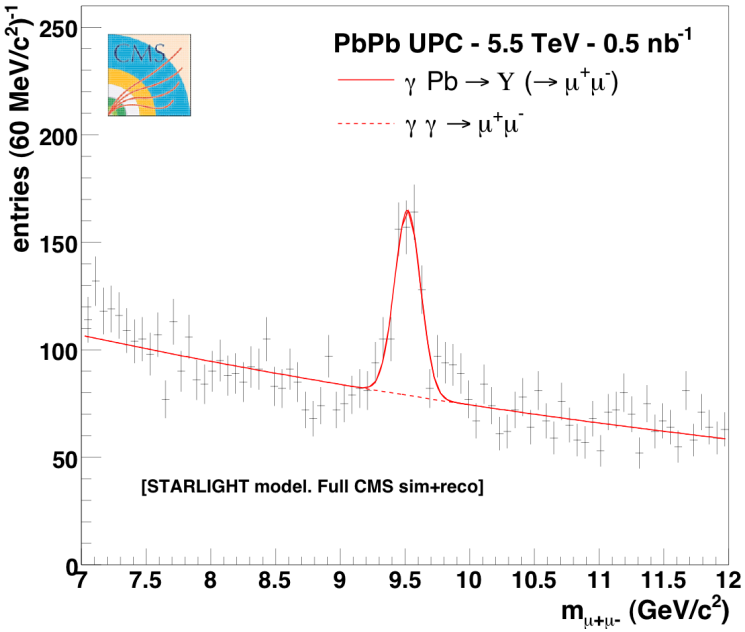
- **signal to background** ratio

$$\frac{N_{signal}}{N_{continuum}} = \frac{\sigma_{PbPb\to\gamma Pb\to\gamma} \times BR(\Upsilon \to l^+l^-)}{\sigma_{PbPb\to\gamma\gamma\to l^+l^-(m_{inv}=6-12GeV/c^2)}} \approx 0.35\%(0.15\%) for \mu^+\mu^-(e^+e^-)$$

- **full** CMS simulation and reconstruction



Peak position: ∼9.35 GeV
Mass resolution:∼ 150 MeV

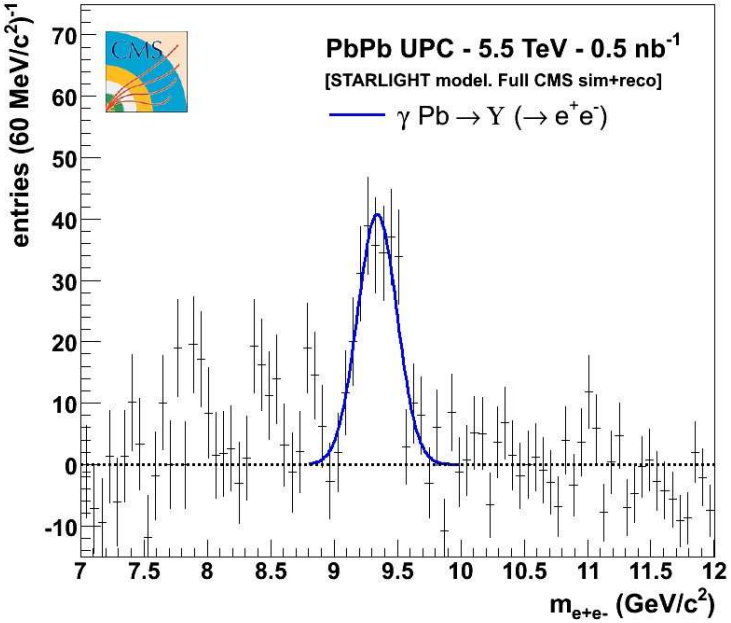


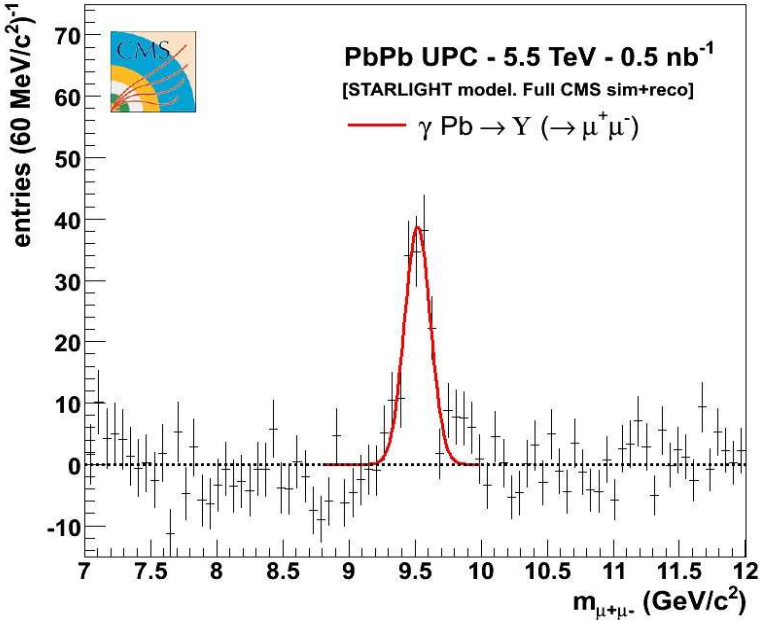
Peak position: ∼9.52 GeV
Mass resolution:∼ 90 MeV

Excellent mass resolution ⇒ higher $b\bar{b}$ states (not simulated) can be separated

Pb+Pb: extracted yields

- 1 year of Pb+Pb running ($\sim 10^6$ s) with background subtracted





- final rates
  - N($\Upsilon \to e^+e^-$): $\sim$ 220 $\pm$15% (stat) $\pm$ 10% (syst)
  - N($\Upsilon \to \mu^+\mu^-$): $\sim$ 180 $\pm$13% (stat) $\pm$ 10% (syst)

Large statistics for detailed studies of gluon PDF

Summary

- **Non-linear** QCD evolution and gluon saturation **MUST** be taken into account in the high energy limit
- **First signs** of non linear QCD dynamics in HERA (e+p) and RHIC (d+A, A+A)
- **CMS allows** to study high density QCD in p+p/Pb+Pb/p+Pb down to $x \sim 10^{-5}$ using forward detectors and perturbative processes

- CMS detector is **working very well** and taking a **high quality data**
- first **analysis** of p+p data were **performed**: forward jets and energy flow
- we are **looking forward** for more data to perform **detailed studies** of the jets in the **forward region**